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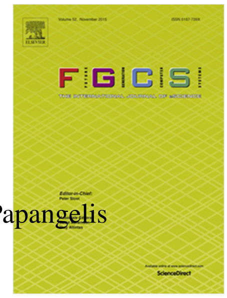

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Evaluating the Effects of Collaboration and Competition in Navigation Tasks and Spatial Knowledge Acquisition within Virtual Reality Environments

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Abstract

Current virtual reality environments, due to their higher viewing resolution and degree of immersion, can help users to acquire spatial knowledge with more ease. In addition, they are considered suitable environments that can facilitate collaborative engagement. With recent advances, we have a new wave of virtual reality technologies in the form of portable head-mounted displays (HMD), like the HTC Vive and Oculus RIFT. In this research, we investigate the effects of collaboration and competition activities, that are carried out within HMD VR environments, on users' navigation behavior and acquisition of spatial knowledge. To do this investigation, we have developed a 3D virtual shopping mall with 3 floors and a number of shops. This mall resembles one that people would normally visit in real life. We then have conducted an experiment with two groups of paired users and one group of single users. Their task is twofold: (1) to navigate within the virtual mall and collect a set of items placed throughout the mall; and (2) to remember the locations of the items and several designated shops. While they have to do this in the shortest time possible, one group of paired users have to work in collaboration with each other, and the other group in competition. Paired users in both groups are physically co-located and are allowed to talk to each other. The third group of users have to work alone. After the experiment, each user is requested to pinpoint the location of the items and shops on a map with the layout of the virtual mall. The results show different patterns of user behavior for the two paired groups and single users. In addition, they indicate gender differences in behavior and performance. Overall, the results help us understand the effects of competition and cooperation in navigation behavior and spatial memory recall using commercial HMD VR systems.

Keywords

Virtual reality; head-mounted displays; collaboration; competition; in-door navigation; visual-spatial memory; user-study

1. Introduction

Navigation is the ability to find one's way around our environment and is one of the most common activities people do in both physical and virtual reality environments [1–4]. Typical environments include in-door buildings such as shopping malls or public museums. People navigate around these environments to locate places of interest for later recall—for example, location of specific shops within the malls [5]. It is not uncommon that while navigating people simultaneously perform other tasks (e.g., talking on the phone or with other people who are accompanying them). Multitasking divides attention, increases cognitive load, and affects memory recall. In the physical world, people acquire environmental spatial knowledge using two common ways: 1) by directly locomoting in the environment, and 2) by viewing maps [4,11,15,19,53]. Both activities allow people to form cognitive maps, which can be used later to support navigating the same environment. In addition, people frequently ask others for directions, and use landmarks and cardinal directions to facilitate finding places and locations [6–8]. Advances in recent developments in immersive virtual reality (VR) technologies provide an alternative way of acquiring spatial knowledge which does not require physical locomotion, but instead uses the interaction with simulated virtual renderings of the environment [9–12].

Immersive VR is a 3D simulation of the real world, one "*in which the computer creates a sensory-immersing environment that interactively responds to and is controlled by the behavior of the user*" [13]. That is, within a VR environment (VE) many of the visual and spatial characteristics are experienced in a similar manner during physical navigation. Current VR technologies are focusing on improving natural realism using high resolution displays and this brings users closer to the feeling of being in the actual physical environment. A new generation of head-mounted displays (HMD), like the Oculus RIFT, HTC Vive and Sony PlayStation VR, are now equipped with high-definition displays and are designed to be used at homes. In addition, mobile VR headsets, like the Samsung Gear VR and Google Daydream View transform a smartphone into a portable VR device to offer more freedom of movements and increase portability. In 1996, Raymond R. Burke coined the term "Virtual Shopping" [14] and these VR devices are touted to be the gadgets that can transform our visits to malls and people's shopping experiences. Recently, in an online article published in October 2017, the technology incubator arm of Walmart showcased examples of HMD based virtual reality technologies as part of a platform for online shopping, where people could visit a virtual shopping space and perform activities associated to shopping [61]. The company aims to use these technologies to transform the shopping experiences of millions of shoppers in the future. Therefore, with further advances in VR, it is conceivable that in the future visiting a shopping mall and making purchases can be done virtually from one's home via VR HMD. To achieve a positive experience, navigation and the ability to locate and remember shop can be important and warrants further exploration so that we can design suitable interfaces.

In one of the early desktop based VE studies, Richardson et al. demonstrated that the VEs can help people acquire a substantial amount of spatial knowledge compared to map-based navigation or real-world navigation methods [15]. They observed two major challenges in VEs: (1) effectiveness of the navigation heavily depends on the realisms of the displayed environment; and (2) the difficulties associated with moving around the VE. In VEs, this moving around has two parts: (1) *travel*, often referred as the physical control of the user's viewpoint; and (2) *wayfinding*, the cognitive process of defining a path through the environment [2,3]. Recent commercial HMD support mainly virtual travel via the use of head tracking for orientation and some other input devices (like a game controller) for manipulating viewpoint positions. In this paper, because our emphasis is on commercial HMD, we focus on virtual travel.

In parallel, 3D VEs are places where people can interact with each other [16,17]. This interaction with other people must by necessity not be neutral but can affect their engagement with the environment [18–20]. For example, VEs are often viewed as platforms for people to engage in group collaborative learning and knowledge acquisition [17,21,22]. On the other hand, interactions within VEs can also be of a competitive nature, as in the case of multiplayer games [23]. The collaborative approach in VR also allows people to acquire spatial knowledge—that is, the presence of others influences the acquisition of spatial knowledge [24]. The focus of this research is to explore how both competition and cooperation interactions affect people's navigation behavior within VEs and their memory recall of spatial information (such as the location of shops).

In this research, we aim to increase our understanding of how users' navigation in VEs using HMD is impacted when they are working synchronously in competitive and collaborative contexts. In addition, because research seems to indicate that there is a distinction between female and male users not only in spatial navigation and memory abilities [25–30] but also in their attitude towards competitive or collaborative tasks [31], we want to know if gender plays a significant role when navigation is performed as a competitive or collaborative activity. In short, this research aims to answer two questions: (1) how users' navigation within VEs and their memory recall of spatial information are affected when they are competing or collaborating with another user; and (2) what role gender plays in users' competitive and collaborative navigation behavior and their recall of spatial information afterwards.

2. Background and related work

2.1. Navigation and visual-spatial memory

Navigation in general is a way of extracting information which combines both the *cognitive* (wayfinding) and *motion* (motoric) elements [32]. In computer-generated 3D VEs, navigation is achieved through different display and input modalities [33,34]. There are many ways to acquire spatial knowledge from any environment. Lynch [35], for example, drawing from research on navigating cities suggests that *landmarks* are the most important cues in any environment to build spatial knowledge. The relationship between navigation abilities and spatial memory has been researched extensively [36]. This research shows that there are individual and group differences in navigation practices and spatial abilities, particularly for males and females [2,3,6,25,37–40]. For instance, Voyer et al. [38] have conducted a recent meta-analysis of research papers and found that in tasks requiring visual spatial memory, females have been found to do better for spatial location tasks only, where males emerged with a significant advantage for all other tasks, especially when the tasks are performed on computers as opposed to using physical media. Because their analysis has not looked at the relationship between spatial memory and navigation, it is unclear whether the female advantage remains for tasks involving more than one person.

In this research we are concerned with visual-spatial memory because it affects how people navigate their environment and their later recollection [36,38]. The term memory has been explored from a variety of angles and researchers in cognitive sciences and cognate areas have proposed various models and definitions [3,36,41,42]. To frame our research, we use the definition from Voyer et al. [38], who have defined it as "*the process involved in the storage of spatial or visual information over a limited period of time*" (p.309). The reason we use this definition is because visual-spatial memory skills involve the ability to recall and recognize shapes and colors as well as the locations of objects and path movements within a space, either virtual or real. We also want to stay away from any specific theories and have a broad definition that reflects the main aim of our research.

We want to focus on navigation within VEs involving competition and collaboration activities with paired users because of two important reasons. First, VR technologies are meant for both genders, as females and males are frequent users of popular 3D VEs like

SecondLife [43] and both have shown interest to use VR in the future [44]—both factors would suggest a positive reception. Second, VR technologies are also meant to be gadgets for social interaction—in fact, they are meant to take social *virtual* interaction to the next level. Social, collective shopping and navigation of malls similar to what people do in actual, real life could be part of future VR-supported activities which allow multiple users to participate in shopping experiences. Having a good understanding would allow us to design VR technologies and activities that are supportive of group navigation needs.

2.2. Navigation in VR

3D Navigation has been studied in traditional TV/computer displays and CAVE-type 3D environments [45–48]. Research suggests that immersion is key to having enhanced experiences navigating 3D spaces in the context of 2D screens. For example, Tan et al. [46], from a series of studies involving users in navigating 3D spaces but using 2D displays, have reported several advantages of using large displays as compared to smaller, desktop size screens. Due to the bigger size of the displays, users felt a greater sense of immersion and that helped them develop better cognitive maps of the virtual worlds. Their participants were able to rely on the mental maps to perform better in their navigation tasks in 3D environments. Similar research is also reported by Bakdash et al. [49]. HMD, like the Oculus RIFT, are intended to provide an even higher level of immersion and as such are thought to be suitable means to support navigating 3D virtual spaces; hence, here lies our interest in the use of the HMD to explore collaborative and competitive tasks in such spaces.

Navigation in VEs can be categorized broadly as *walking around* or *flying over* [50]. In this research, our focus is on *walking*, and more specifically on *virtual walking* and not *real walking* [51,52]. Real walking allows users to travel by navigating the VE in a natural manner, just as they would do physically. In VEs this is achieved by either having a large physical space in which users' movements are tracked and mapped onto the VE or having their physical motions of walking simulated using mechanical devices such as treadmills. Although the real-walking approach has shown to have positive effects on navigation [2,53], but, because of the extra technological and large physical space requirements, this approach is not practical outside of research labs and thus not supported by popular commercial HMD. Virtual walking, on the other hand, refers to travelling within a VE that do not imitate exact physical movements but using controls such as a game controller to perform navigational tasks—for example, changing of viewports or moving around is achieved through joysticks. By using such control devices, it is possible to have arbitrarily large virtual environments when using a small physical workspace and without the need to have additional tracking devices [54].

There has been some research looking at collaboration activities in 3D VEs. These environments can provide support for asynchronous and synchronous collaborative activities [21]. Some collaborative VR systems use the "*spatial model of interaction*" [16] to support users' presence and enable awareness of each other to increase opportunities for interactions [24,55]. Non-verbal communications can also be supported in collaborative VR systems [56]. Our research, in addition to exploring collaboration, looks also at competition and how these two activities affect users' navigation behavior and spatial memory recall of objects in the VE. To the best of our knowledge, we have not yet seen this kind of studies, which juxtaposes these two activities. Results can increase our understanding of multi-user VR systems and enable their design to be more supportive of users' navigation activities.

3. Experimental design

To investigate the effects of collaboration and competition activities on navigation behavior and spatial memory recall, we developed a 3D virtual shopping mall and conducted a user study involving three groups. In this section, we provide details about the 3D VE, participants, and the procedure. The section after presents the results.

3.1. Apparatus and participants

We developed a multi-user 3D VE in Unity3D. The environment was a three-floor vertical shopping mall populated with well-known, popular stores. The 3D model followed the standard design approaches found in the urban vertical shopping malls with stacked, vertical floors. The shops were labelled with clear and unobstructed signs. There were moving stairways (escalators) in the middle of the environment to allow users to reach every floor. Two users could navigate in the environment at the same time. Each user had an avatar representation, and this would allow one user to know the other user's location and direction of travel (see Figure 1). The items to be found and collected by participants appeared in the corridors of each level as rotating cubes. The table in the interface was used to highlight the list of items collected by each participant. The two squares on each side would show the direction of the game joystick—the controller used in the experiment—to help improve navigational awareness of participants. To have consistency across the groups and participants, the same area near the stairways on the second floor was set as the starting position.

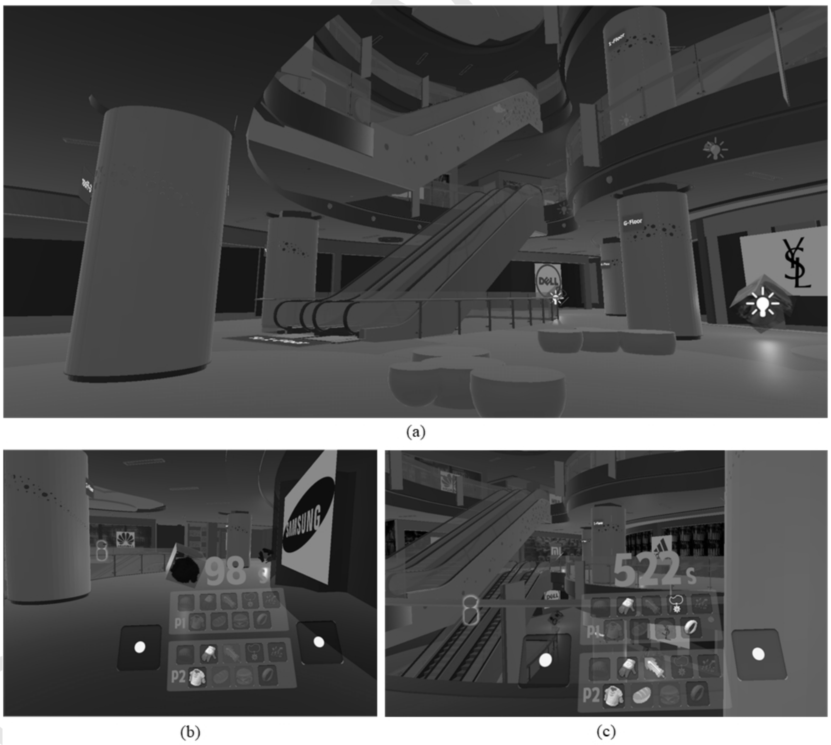


Figure 1. Screenshots of the 3D environment with 3 floors (a, c, b). The items that had been collected and still had to be collected were displayed in the table in the lower part. When viewed using the HMD, the number of seconds elapsed, and the items were displayed with 3D perspective effect. The mall was populated with signs of easily recognizable shops. Each floor was labelled with clear and conspicuous (red) signs. When working in pairs, an avatar was used to represent its location—see the (green) silhouette (c).

The complete implementation of the VE was completed in Autodesk 3DS Max and Unity3D. The initial 3D modeling of the shopping mall was done using 3DS Max, followed by numerous Unity3D scripts to implement the virtual walking, multi-user features, and a table displaying the found and yet-to-be-found items. The Unity3D's built-in "FPS Controller" is used to achieve realistic walking experience. We used the "Photon Network"[1] plugin to complete the multi-user feature. The table in the VE was developed using "Inventory Master"[2] while the glowing effect of the avatar is achieved by the "Highlighting System"[3]. The complete development of our 3D virtual shopping mall took about 3 months.

The experiment was run using two desktop computers, each one with an i7 CPU running at 4 GHz and a GTX1070 dedicated GPU. A set of Oculus Rift CV1 was attached to each. The two workstations were placed adjacent to each other in the same lab space (see Figure 6a below). This setup allowed participants to communicate with each other without any mediation. During the experiment, the two systems were networked and connected to a local server to allow two users to be in the same VE. The left joystick on the Xbox One controller was used to allow users control the navigation movements in the VE (See Figure 2).

Figure 2. The Xbox One Controller and its LEFT Joystick was used for moving the avatar in VE.

We recruited 25 participants (15 males) between 20-22 years old (*M* = 21; *SD* = 1.2) from a local university. They were all undergraduate students and had volunteered to do the experiment. A between-groups design was used with participants randomly allocated to 3 groups: COOPERATION (COO), COMPETITION (COM), and SINGLE (SIN). This meant that each participant was involved in only one of the three groups. Both COO and COM groups had 10 participants who were randomly paired—that is, 5 pairs in each group—and would either sit or stand next each other during the experiment (see next section for further details). The SIN group has 5 participants who interacted with the system as single users. There was at least one pair of female participants for both COO and COM groups and there were 3 female participants in the SIN group (see Table 1 for the distribution of participants).

[1] https://www.assetstore.unity3d.com/en/#!/content/1786
[2] https://www.assetstore.unity3d.com/en/#!/content/26310
[3] https://www.assetstore.unity3d.com/en/#!/content/41508

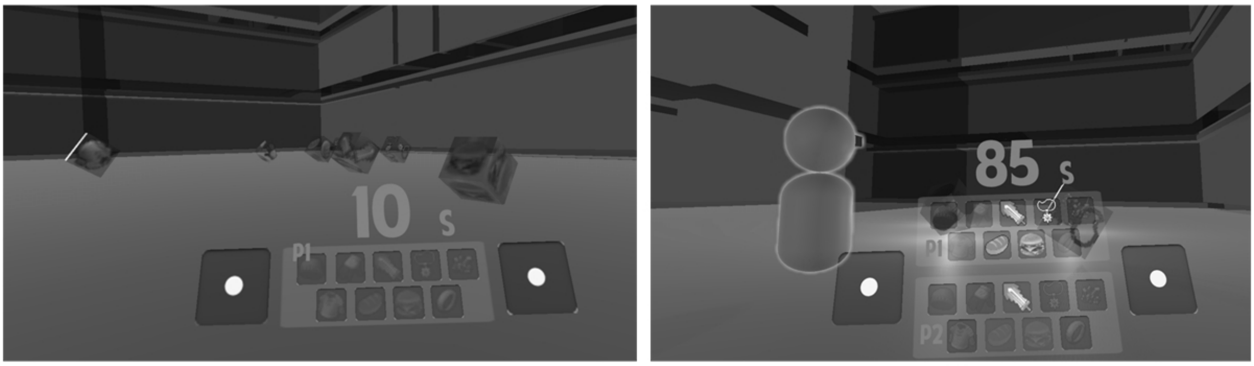
Table 1: Distribution of male and female participants in all three groups.

Groups	**Size (N)**	**Male (N)**	**Female (N)**
Single (SIN)	5	2	3
Cooperative (COO)	10 (5 Pairs)	5	5
Competitive (COM)	10 (5 Pairs)	8	2

3.2. Task, Procedure, and Design

There were four phases of the experiment: (1) understanding the requirements of the study; (2) participants' familiarization of the VE and input device; (3) two-stage experiment; and (4) the exit questionnaire. In the first phase, participants were asked to complete a pre-study questionnaire to collect demographic information and prior experience with VR environments. After, they were told about the experiment. In addition, an information sheet with pictures of the 9 items and logo of 10 shops used in the experiment were shown to participants.

In the second phase, participants were first asked to practice using another multi-user 3D environment (see Figure 3) to familiarize themselves with a similar environment and the virtual travel features, the VR HMD, and Xbox controller. The table interface in the practice VE was identical to the actual VE of the experiment. The participants were asked to navigate around the environment to pick the items and were able to see the other participant in the form of an avatar representation. The same animated items, 3D rotating cube, were displayed and scattered on the floor. For the SIN condition, the items would disappear after being picked up. For COO and COM conditions, the color of the item would change to blue and its rotation would stop when the item was picked by one participant and it would completely disappear when picked by both participants. The collected and uncollected items were always displayed in the middle table (see Figure 3). When the participants completed the collection of items, the practice session would then terminate. For COO and COM conditions, the participants were instructed to pay close attention to the table and how the animation of the items would appear in the VE when the item was collected by the other participant. This practice session took 5-10 minutes and, if requested, participants could have more time to practice. No participants reported any difficulties or issues wearing the HMD, navigating the VR environment, or using the Xbox controller.



(a) (b)

Figure 3. (a) Screenshot of the SIN participants' practice 3D environment with the items on the floor and table showing the collected and uncollected items. (b) Screenshot of the COO and COM participants' practice 3D environment with all items and table. When working in pairs, an avatar was used to represent its location—see the (orange) silhouette.

In the third phase, a two-stage experiment was conducted with the three groups. The COO pairs were told that they '*can*' work together to collect the set of 9 unique items (see Figure 4 below) placed throughout the environment—the implication was that they should try to collaborate with each other to locate the items. The COM participants were told to collect the items as quickly as possible and were not restricted to speaking with each other. COM participants understood that there was a competitive element and that they ought to be faster than the other participant in collecting the items. In both COO and COM conditions, the pairs interacted within the VE at the same time and in a collocated manner—that is, they were standing or sitting next to each other. Their conversations were recorded with their permission. The 5 SIN participants were the control group. All participants were asked to remember the location of the 9 items and 10 shops that populated the virtual mall (see Figure 4 below). The number of items was informed by Miller's Law [59], which suggest that what an average human can hold in working memory is 7 ± 2 items. Shops were included to enhance the complexity and increase the diversity of elements to be remembered by participants. In addition, they would reflect a common scenario of visiting a shopping mall, one in which people would need to remember the location of shops of their interest for later recall.

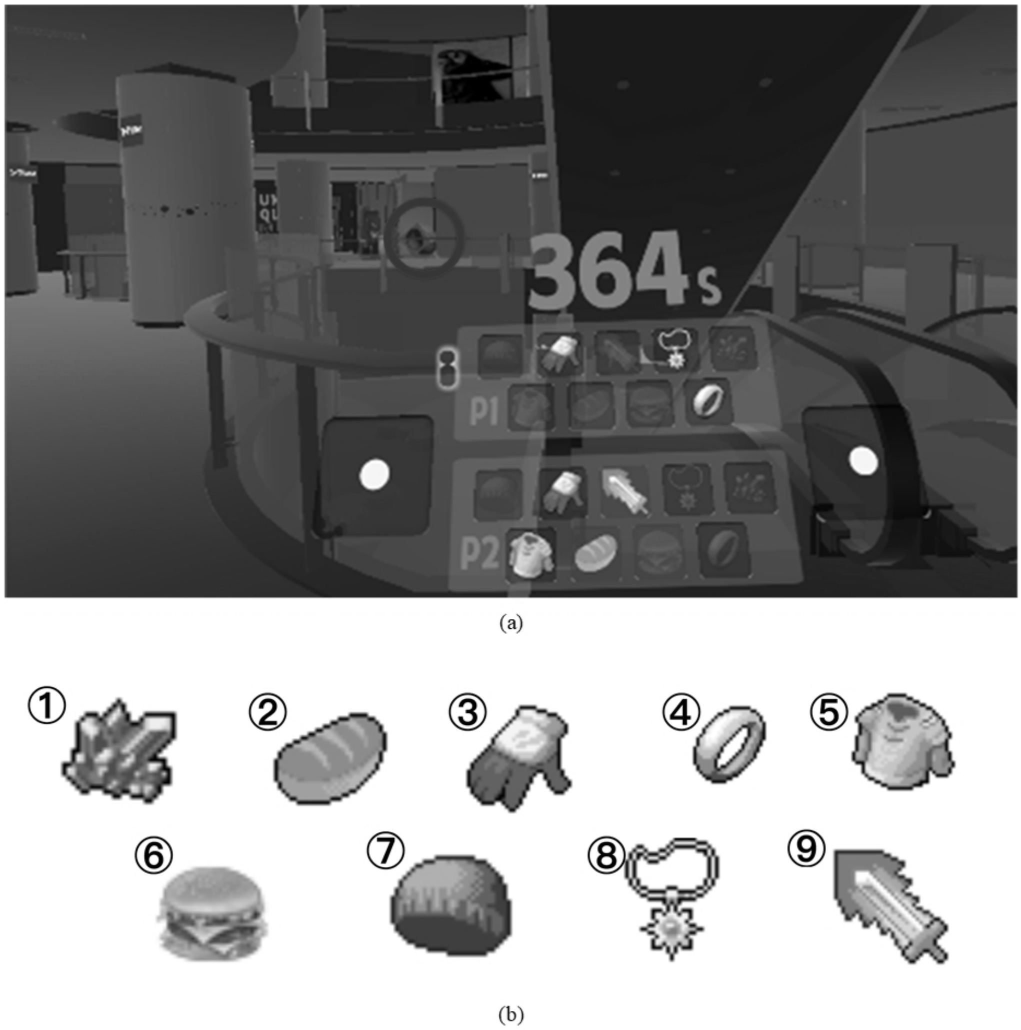


Figure 4. The items to be found and collected by participants. (a) One of the items displayed at a distance in the environment whose view is obstructed by stairs—see the (red) circle in the middle of the figure. For a close-up view of another item, see previous Figure 1b.

The 9 items were distributed evenly in the three floors—3 items on each floor—and were positioned to make participants cover all the locations where there were shops that participants would need to recall later. Three shops were placed on the ground and second floors each and the remaining four shops were placed on the first floor (see Figure 5 for the shop labels used). Participants had no prior knowledge of their distribution and exact location.

Participants in COO and COM groups would do the experiment either standing or sitting next to each other and would begin in the same location within the VE. Each participant was able to see the other participant's location in the VE in the form of an avatar figure (see Figure 4a above, and Figure 6b below). Similar to the practice VE, items in SIN group would disappear once collected. For the COO and COM groups, the items had two visual states. When the item was collected by one participant, it would turn blue and its rotation would also stop. The item would completely disappear when it was collected by both participants. The list of items collected was also highlighted on table in the middle of the interface. This approach was meant to allow awareness of the items collected and still-to-be collected by each participant. The participants should be familiar with this process, as they had prior experience from the practice session before the experiment.

Figure 5. Labels and signs of the 10 shops that populated the mall. The shop labels were all familiar to participants and were shown to them prior to the experiment to make sure they become acquainted with them.

The time it took to collect each item was recorded by the system. After finishing the experiment, participants would then move to the second stage of the third phase: the completion of the memory test, which would require them to locate the shops and items on a map with the layout of the shopping mall (see Figure 7). On this map, shops were represented as empty rectangles and items as diamonds or small squares. During the test, participants were once again given access to information sheet with the list of items and labels of shops.

Figure 6. (a) A picture of two participants interacting with the VE in the COM group. (b) A screenshot of how a user avatar looked like within the VR headset. Figures 1c and 4 show the avatar in (green) color when the user is further away.

The fourth and last phase was an exit questionnaire. After the memory test, participants were asked to complete an exit questionnaire to collect their opinions of their interaction with the environment. The four phases of the experiment took approximately 50 minutes to complete.

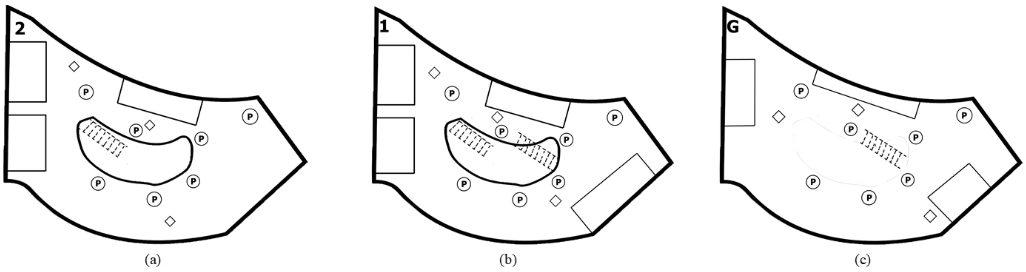


Figure 7. The 2D paper maps of each floor on which participants were asked to specify the locations of the shops and items they collected. (a) Second floor, (b) First floor, and (c) Ground floor. Shops were represented as rectangles and items as diamonds.

4. Results

The recorded data were analyzed using two-factor (Group x Gender) between participants ANOVA tests followed by Tukey HSD post-hoc comparisons, unless noted otherwise. Type III Sums of Squares calculation was used, which was appropriate for an unbalanced design due to the nature of the three groups. We first compared the time spent and distance traveled. Then, we tested participants' recollection of the locations of the items they collected and of the shops in the mall.

4.1. Time spent and distance travelled

The first aspect that we wanted to assess was navigational efficiency by looking at the time spent, and distance travelled. On average, COM participants used the least amount of time but walked the most (see Figure 8 below); the SIN group walked the least and used the least amount of time; COO participants spent the most amount of time and their distance walked felt between the two other groups.

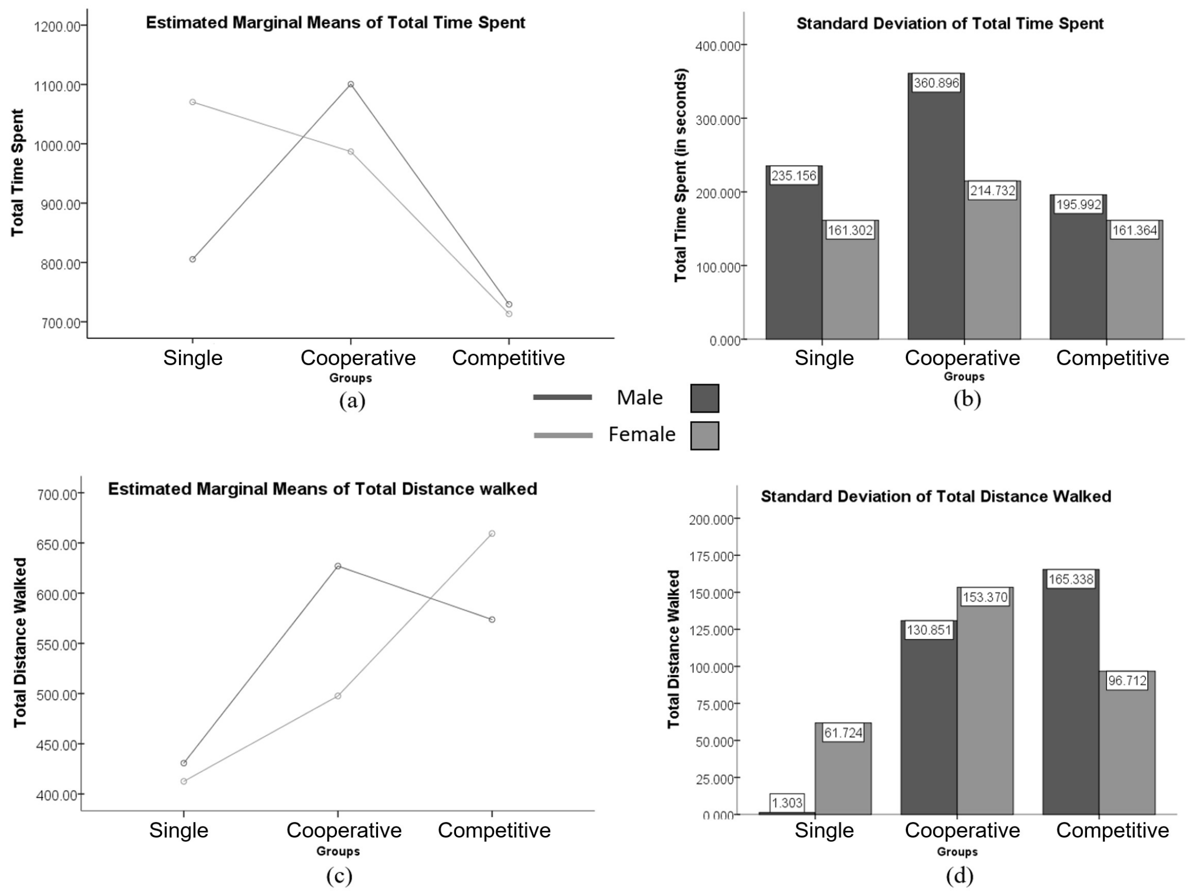


Figure 8. (a) and (b) The average total time spent (in seconds); and (c) and (d) total distance travelled based on *Group* and *Gender*.

ANOVA tests showed there was a borderline conventional significant effect for Group, $F_{2,19} = 3.492$, $p = .051$; the COM participants ($M = 726.09$, $SD = 181.15$) spent the least amount of time followed by SIN participant ($M = 964.36$, $SD = 218.87$) and then by COO participants ($M = 1{,}043.71$, $SD = 286.30$). There were no significant effects for Gender, $F_{1,19} = .169$, $p = .686$. There were no significant interactions between Group and Gender, $F_{2,19} = 1.003$, $p = .385$. Post-hoc tests indicated that participants in COM finished significantly faster than COO participants, $p = .022$ but not for participants in COM/SIN and SIN/COO groups (both $p > .05$).

Participants' locations in the 3D environment were recorded at small time intervals. These data were then used to calculate the distance covered by each participant. ANOVA tests showed no main and interaction effects for Group ($F_{2,19} = 2.78$, $p = .087$) for SIN ($M = 419.84$, $SD = 44.76$), COO ($M = 562.29$, $SD = 150.70$) and COM ($M = 590.81$, $SD = 153.64$).

4.2. Items and shops remembered

The second aspect we wanted to assess was participants' memory recall of the locations of shops and items collected. As stated earlier, we asked participants explicitly to remember the locations of the items and shops. Their responses would be used indirectly to gauge the effect of the VR environment on their acquired spatial memory. On average, SIN participants did better, followed by COO participants, and finally by COM participants at the end (see Figure 9 below).

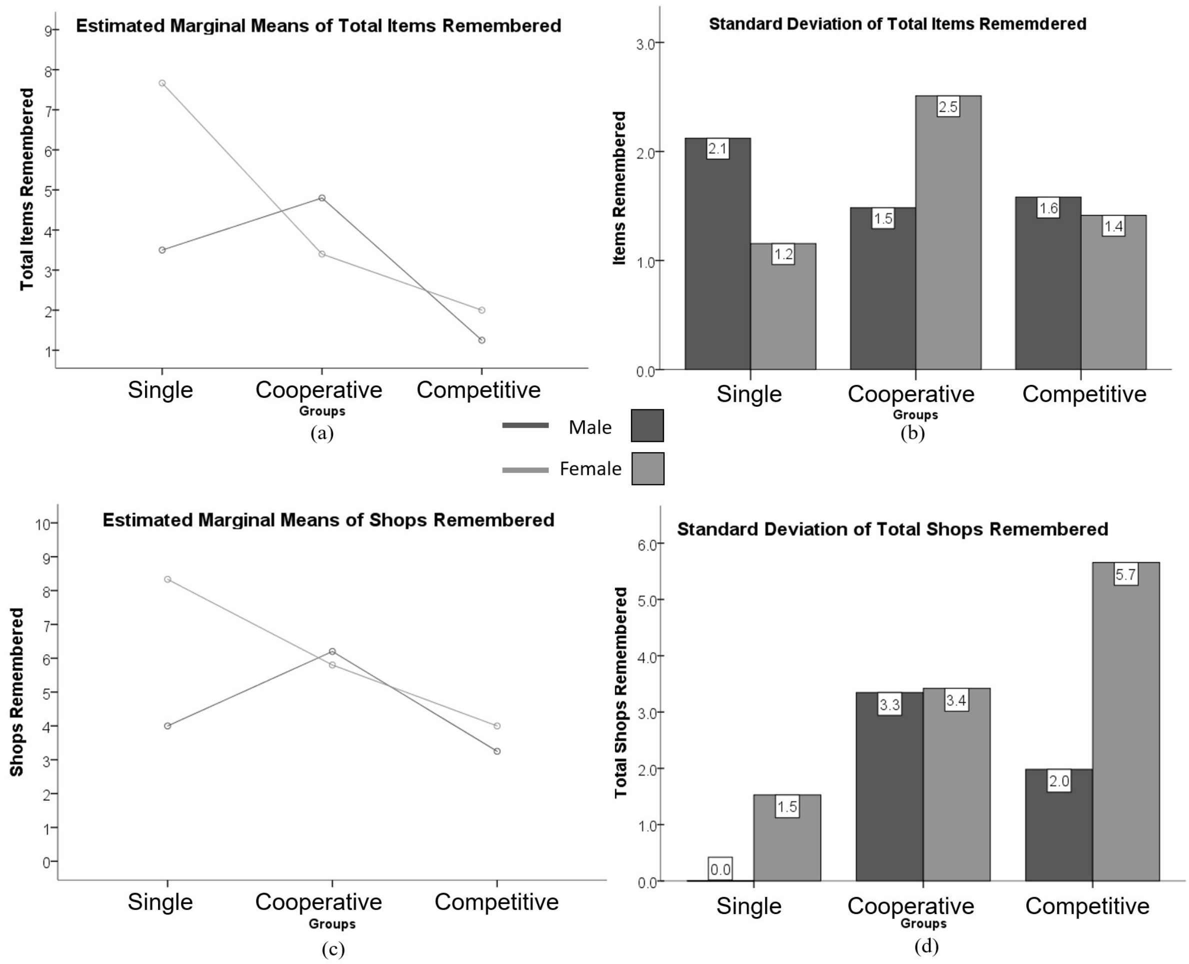


Figure 9. (a) The Items remembered and (b) Shops remembered based on *Group* and *Gender*.

ANOVA tests showed significant effects on items remembered of Group, $F_{2, 19} = 7.231$, $p = .005$, but not of Gender, $F_{1, 19} = 2.084$, $p = .165$. Interaction effects were also found, $F_{2, 19} = 3.955$, $p = .037$. The results indicated that there was a significant difference between participants within SIN ($M = 6.0$, $SD = 2.65$), COO ($M = 4.10$, $SD = 2.08$), and COM ($M = 1.40$, $SD = 1.506$). Post-hoc comparisons showed that participants in both SIN and COO groups remembered significantly more items than those in COM, both $p < .009$.

On the other hand, ANOVA tests on shop remembered also yielded no significant main effects of Group for SIN ($M = 6.60$, $SD = 2.60$), COO ($M = 6.00$, $SD = 3.19$) and COM ($M = 3.40$, $SD = 2.59$) and of Gender for Male ($M = 4.33$, $SD = 2.66$) and Female ($M = 6.20$, $SD = 3.45$).

People's motivation and attention can decline over time, which can affect their memory recall. We checked this by looking at how well participants were able to remember the items and shops on a floor-by-floor basis. In our study, all participants would begin in the same area on the second floor. They would then normally go to the first floor and finally to the ground floor. Although they could skip floors, we observed that participants would navigate floor by floor in the same sequence, without skipping. Table 2 below summarizes the test results.

	Floors	Groups	Gender	Group x Gender
Items	Second	.073	.870	.248
	First	**.001**	**.017**	.135
	Ground	**.018**	.282	**.042**
Shops	Second	.572	.089	**.018**
	First	.379	.114	.942
	Ground	.127	.562	.825

Table 2. *p* values from t-test results within each group. Significant values are highlighted.

For items on the second floor, although the ANOVA test resulted in a barely detectable statistically significant effect of Group, $F_{2,19} = 3.015$, $p = .073$, post-hoc tests indicated significant differences for participants in SIN ($M = 2.60$, $SD = .894$) and COM ($M = .80$, $SD = .919$), $p = .020$. On the second floor, there were significant effects of Group, $F_{2,19} = 15.509$, $p < .0001$, and Gender, $F_{1,19} = 6.901$, $p = .017$. Post-hoc tests showed that participants in SIN ($M = 2.40$, $SD = .894$) did significant better than those in COO ($M = .80$, $SD = .422$) and COM ($M = .40$, $SD = .699$). Finally, on the ground floor, there were significant effects of Group, $F_{2,19} = 4.977$, $p = .018$, and Group x Gender, $F_{2,19} = 3.766$, $p = .042$. Post-hoc tests showed participants in COO ($M = 1.60$, $SD = 1.075$) did significantly better than those in COM ($M = .20$, $SD = .422$), $p = .003$.

For shops remembered correctly, surprisingly, there were significant effects on the shops on the second floor of Group x Gender, $F_{2,19} = 4.976$, $p = .018$. However, post-hoc pair-wise tests showed no significant effects.

Although we did not find clear effects of Group and Gender for items and shops, when we plotted the data, we could observe some notable patterns (see figures 10 and 11 below). Participants in SIN would normally performed relatively well in items/shops on the second floor, but this would decline over time. The performance of participants in COO tended to improve over time. Finally, the performance of those in COM would remain the same and low across the three floors.

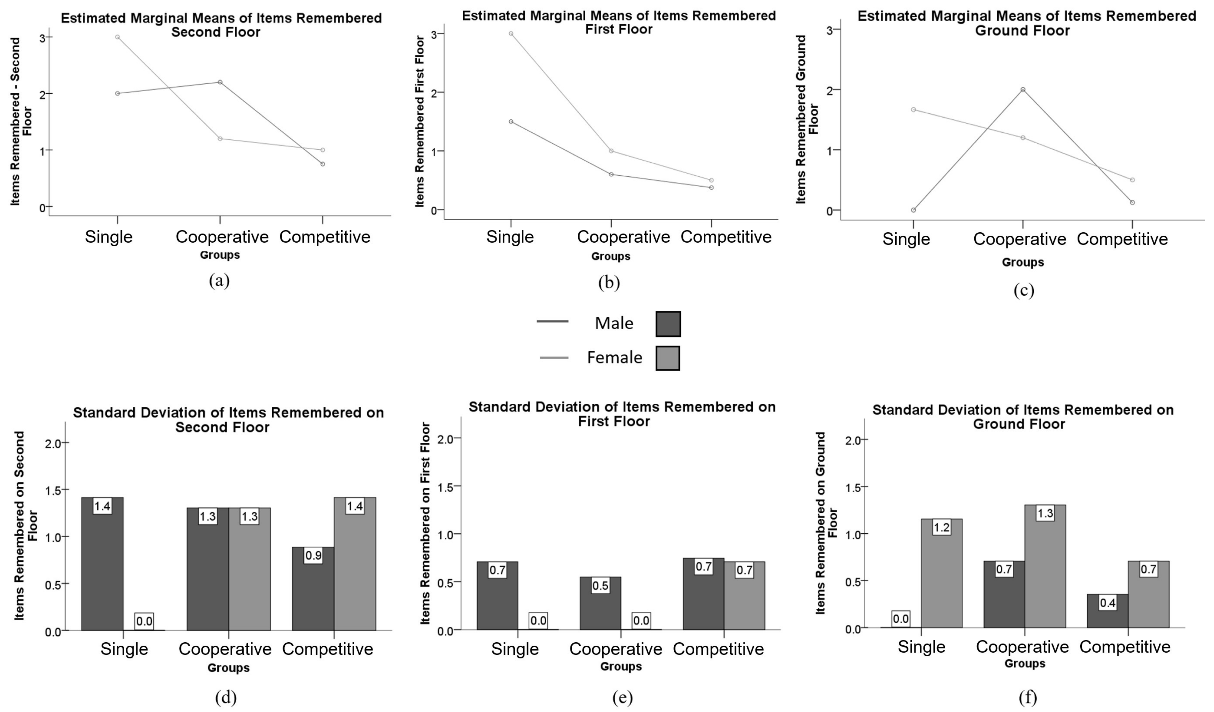


Figure 10. Items remembered per floor based on *Group* and *Gender*.

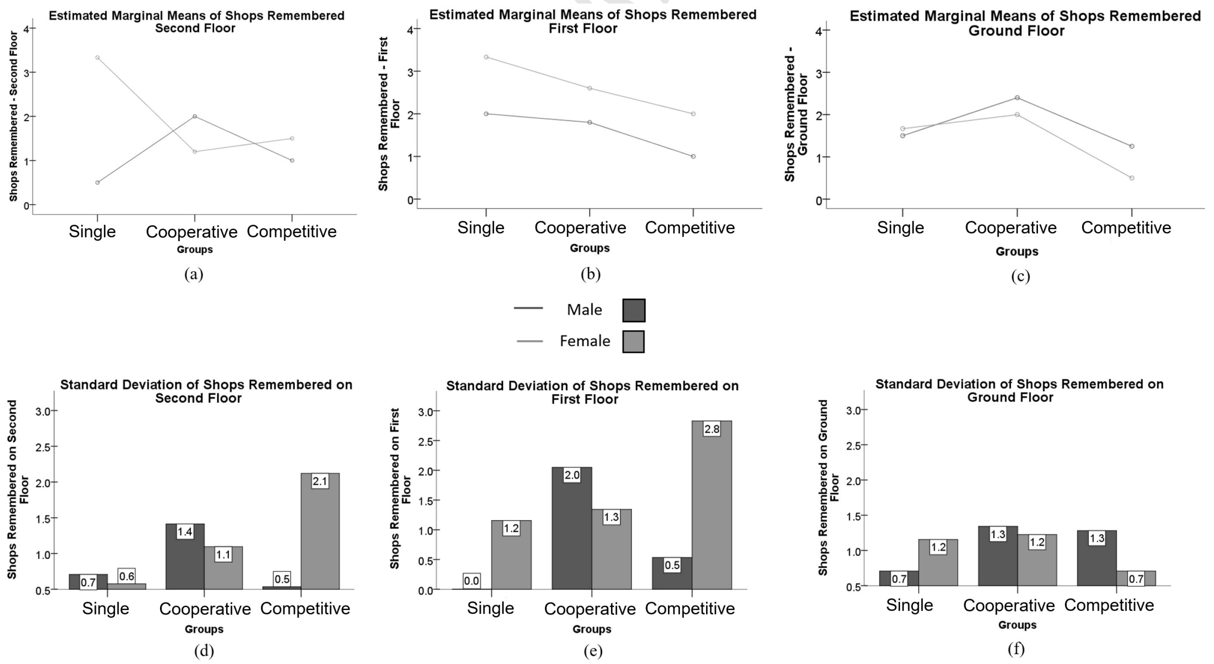


Figure 11. Shops remembered per floor based on *Group* and *Gender*.

Finally, we wanted to look at the effects of gender in each one of the groups for time spent, distances walked, and items/shops remembered. We conducted t-tests within each group. No significant effects were found for time spent and distance walked. The tests indicated significant effects in shops remembered for Females (M = 8.33, SD = 1.53) and Males (M =

4.0, *SD* = .00) in SIN group, $t(3) = 3.806$, $p = .032$. There were very close to approaching significant effects in items remembered for Females (*M* = 7.67, *SD* = 1.16) and Males (*M* = 3.50, *SD* = 2.12) in SIN group, $t(3) = 2.953$, $p = .060$. Females in both COO and COM groups walked less (412.58 vs 430.74) but used more time (1,070.37 vs 805.36).

4.3. *Patterns of behavior*

The three groups of participants exhibited different types of behavior.

Competition. There was not much communication among these participants, although we never mentioned to these participants that they could or should not talk with each other. Each participant was always trying to navigate as fast as possible to collect the items faster than other participant. They did not slow down or stop to observe their surroundings. This could explain their time performance, and how much extra distance they walked in the VE.

Cooperation. From the beginning the pairs of participants talked about what they saw, shared their observations of their surroundings, and planned their next move. The five pairs of participants often told each other, "*Should we go to the next floor*," "*Is there anything left on this floor*," and "*Did you see any items over that end*". They would freely share their locations and items found and were observed sharing tasks with example expressions like "*you go find the items in that area*," and "*why don't you go to that area to check the shops first, and I will follow you later*". In mixed-gender pairs, the male normally would take the lead and the female participant became the follower. In groups of two female or male participants, they would share roles interchangeably. Finally, these pairs would double check together the locations of shops and locations where items were located to help them remember them.

Single. Like the participants in the COM group, these participants were observed to be very focused on locating the items. In contrast, they were also observing their surroundings to see the shop signs. They did not make any sounds and did not ask any questions to the researchers, although we told them they could ask questions if they had any.

5. Discussion and conclusions

In this section, we present the general findings and provide some directions for future research.

In terms of efficiency, participants in COM performed significantly faster than those in COO. This was expected due to their implicit understanding of the competitive nature. In post-experiment interviews, when asked why they moved so quickly through the environment, some participants said that they wanted to be faster than the other person, while others said they wanted to win and did not want to be losing to the other participant. It was unexpected, however, that there was not significant difference for participants in SIN/COM and COO/SIN. This would mean that participants in SIN were nearly as efficient as those in COM. At the same time, participants in COO did not spend significantly more time than those in SIN, despite the COO participants putting effort and time into sharing information and supporting each other. This implies that participants in COO were able to compensate the time used for collaboration with the help they provided to each other in locating the items.

On a closer examination, COM participants were not that efficient as they walked more than the other participants—the extra walking was provisionally significant. On the other hand, SIN participants walked the least. COO participants walked less than COM participants, even though some participants in the former group did extra rounds intentionally to increase their chances of recalling the locations of items and shops.

Despite the amount of walking COM participants were able to remember the lowest number items ($M = 1.4$) and shops ($M = 3.4$). This implies that stress and the competitive nature among these participants could have significantly affected their acquisition and storage of newly acquired information [57]. Both COO ($M = 4.1$) and SIN ($M = 6.0$) groups were significantly better at remembering the locations of items correctly. Although there was not a significant difference in the number of shops remembered, COM participants underperformed the other groups ($M = 3.4$). Interestingly, SIN participants were able to outperform the other two groups ($M = 6.6$). This would imply that SIN participants were efficient, at least marginally more than even COO participants ($M = 6.0$).

Another interesting finding was that although SIN participants were able to remember marginally more items and shops, our above analysis based on each floor indicated that these participants' motivation and focus seemed to decline over time. The analysis indicated the opposite trend for COO participants who were able to remember more items and shops on the lower floors. This would imply that cooperation could engage participants in prolonged focus and engagement with the environment. COM participants saw neither declined nor improved focus.

Our experiment found no significant effects between female and male participants. A recent meta-analysis of papers that investigated sex differences in visual-spatial working memory has found that females could have an advantage on location tasks only [1]. Our results seemed to align with their findings, but we only found this for individuals in SIN group, as female participants did significantly better at locating the shops and a margin at the edge of significantly better at remembering the location of items correctly. However, given the small sample of our study, we cannot generalize this observation beyond the context of our experiment. In the COO group, female participants did equally well as male participants. The same results were found also in the COM group. The results would appear to suggest that female participants functioned well in isolation and also working with another person.

Furthermore, we also noticed that when a female was paired with a male participant, the former tended to take a passive role, with the latter having a more leading, active attitude. This pattern could be down to culture because our experiment was conducted with Chinese students studying at an English-based international university. Despite this, our finding is aligned with previous research on passive and active navigation which suggests that the more active people are, the better they do in spatial knowledge tests and recall tasks [58]. This could explain why the female participants in the SIN group were able to do better at the memory recall tests than the female participants in the other groups because, as we observed, they tended to take a more active role.

On the application level, our results can inform the design of VR interfaces dealing with navigation for information seeking and memory recall. Our results suggest the following four design guidelines:

- *DG1*. If the goal is to maximize memory recall of information, frame navigation activities based on single users and, when dealing with pairs of users, frame them in a collaborative context.

- *DG2*. If the goal of to minimize navigation time for paired users, provide a competitive task scenario.
- *DG3*. If the goal is to maximize memory recall of spatial information, it is perhaps better not to provide competitive tasks to pair of users.
- *DG4*. When users need to explore a large VR environment, pair users in a collaborative task scenario.

There are three limitations with our experiment. The first limitation is our 3D VE: we conducted our experiment within one type of VE, an indoor shopping mall. Although we can address this limitation by designing a different VE like an outdoor outlet mall, we expect our results about time used, distance travelled, and sustained focus over time to remain valid. The second limitation about the VE is its size. Before deciding on the final design and size of the shopping mall, we had checked several studies looking at the size of the VEs. Our mall is bigger than the room-size VE in some experiments and is based on a medium size mall that local shoppers would frequent. Due to its size, we were able to place items and shops in locations with some distance from one another; we have been able to have items and shops not directly visible to participants but are occluded from view (by columns for example). The third and final limitation is the small size of the sample population, although this is not unusual for this type of study (see [60]). In the future, we plan to conduct further studies with a larger population size, and focus on gender differences, navigation in VEs, and spatial cognition.

To conclude, this research complements the existing work on navigation within virtual environments for head-mounted displays. It advances our understanding of the effect of cooperation and competition activities within these environments on navigation behavior and spatial memory acquisition. The results of our study are applicable to the design for single and dual-user virtual reality systems where spatial navigation and memory recall are important.

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Highlights

- We evaluated the effects on navigation behavior and acquisition of spatial memory for single and pairs of users in virtual reality 3D environments.
- Paired users were tasked to either cooperate or compete with one another to locate objects placed throughout the environment; single users worked alone on the task.
- Single participants walked the shortest distance but were still able to remember correctly the locations of the greatest number of items and shops.
- Participants in the competition group walked the longest and took the longest time but could not remember the locations of as many items and shops as the other two groups.
- Participants in the cooperation group felt in between.
- Female participants tended to perform (significantly) better but only in the single group in memory recall.
- Male participants tended to do better in the other two groups.